Production of Beryllium and Boron by Spallation in Supernova Ejecta

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Abstract.
The abundances of beryllium and boron have been measured in halo stars of metallicities as low as [Fe/H] =-3. The observations show that the ratios Be/Fe and B/Fe are independent of metallicity and approximately equal to their solar values over the entire range of observed metallicity. These observations are in contradiction with the predictions of simple models of beryllium and boron production by spallation in the interstellar medium of a well mixed galaxy. We propose that beryllium and boron are produced by spallation in the ejecta of type II supernovae. In our picture, protons and alpha particles are accelerated early in the supernova event and irradiate the heavy elements in the ejecta long before the ejecta mixes with the interstellar medium. We follow the propagation of the accelerated particles with a Monte-Carlo code and find that the energy per spallation reaction is about 5 GeV for a variety of initial particle spectra and ejecta compositions. Reproducing the observed Be/Fe and B/Fe ratios requires roughly 3×10^{47} ergs of accelerated protons and alphas. This is much less than the 10^{51} ergs available in a supernova explosion.

INTRODUCTION

Spallation reactions involving protons or alpha particles colliding with the nuclei of the abundant light elements carbon, nitrogen, and oxygen have long been recognized as important or dominant contributors to the production of the isotopes of lithium, beryllium, and boron (Reeves, Fowler & Hoyle 1970). Evidence for this picture includes the fact that the ratios of abundances of spallation products are equal to the ratios of the production cross sections, the large overabundance of spallation products in cosmic rays, and the fact that the observed cosmic ray flux irradiating a poulation I composition for the age of the galaxy produces the observed spallation to CNO abundance ratio. For a summary of these arguments see the review by Reeves (1982).

Spallation nucleosynthesis in the interstellar medium of a well mixed galaxy is very inefficient if the metallicity of the gas is low. In the simplest closed

box model of galactic chemical evolution, the abundance of spallation products is proportional to the square of the iron abundance at low metallicity. This prediction is contradicted by the observations of beryllium and boron abundances in low metallicity stars (Duncan *et al*. 1992, Gilmore *et al*. 1992, Boesgaard 1996) which show that the Be/Fe and B/Fe ratios are independent of metallicity and approximately equal to their solar values for stars in the metallicity range -1>[Fe/H]>-3.

To account for these observations we propose that spallation nucleosynthesis took place in the supernova event itself. In our model, particles are accelerated and irradiate the CNO nuclei in the supernova ejecta long before the ejecta mixes with the interstellar medium of the early galaxy. We follow the propagation of the accelerated particles with a Monte-Carlo analysis and find that reproducing the observed spallation to iron ratio requires about 3×10^{47} ergs to go into accelerating particles. We also find, not surprisingly, that we produce the same isotopic ratios as are found in calculations which irradiate a solar composition interstellar medium.

MODEL DESCRIPTION & RESULTS

A supernova releases a large amount (10^{51}ergs) of energy as it explodes. A fraction of this energy may go into accelerating particles to very high energies. The type II supernova ejecta are rich in CNO nuclei which serve as targets for spallation by energetic protons and α particles that are accelerated in the expanding ejecta.

We have modelled the spallation production of Li, Be and B in supernova ejecta by writing a Monte-Carlo simulation. The program takes as its input the spectrum of accelerated particles (p, α) in supernova explosion and irradiates the ejecta (CNO) of specified composition and density with these particles.

In the simulation, the accelerated particles start out with initial energy as specified by the spectrum and have elastic, inelastic or spallation collisions based on the probability of that collision according to their relative cross sections and target abundance. The energy dependent cross-sections for these collisions are taken from the compilations by Read & Viola (1984) and Meyer (1971). The main energy loss processes for these accelerated particles are by spallation, ionization and elastic/inelastic collisions. Protons go through

TABLE 1. E_{sp} (GeV) for various E_c (MeV) and n, calculated for a 25M$\odot$ supernova composition

$E_c(MeV) =$	50	100	200	500
n=5	6.3	4.3	5.4	9.6
n=10	4.3	4.2	4.9	8.6

elastic and inelastic collisions with other protons and He nuclei in the ejecta and spallation reactions with CNO nuclei. In the case of a proton-proton or a proton-α elastic collision, the incident proton loses energy to the stationary target and accelerates the target proton or α particle. This creates a cascade of accelerated particles, each of which in turn goes through a sequence of collisions. The energy loss suffered by the incident proton in a proton-proton elastic collision is calculated kinematically using differential cross sections for elastic scattering (Meyer 1971). The proton-proton inelastic collision, p + p $\rightarrow \pi^0$ + p + p, produces π^0s which decay as $\pi^0 \rightarrow \gamma + \gamma$, producing gamma-ray flux. The remaining energy after π^0 production is shared between the two outgoing protons. The proton-α inelastic collision produces secondary particles (d,^{3}He) that are not relevent to our simulation and the incident proton is assumed to lose all its energy. Spallation between protons and CNO produces one of the light element isotopes according to their relative cross sections (p + CNO $\rightarrow$ ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B). Protons also lose energy by ionization in passing through the ejecta. These losses begin to dominate at lower energies. When the ionization energy loss is much greater ($\approx$ 50 times) than the energy loss by other collisions (spallation, elastic and inelastic), the proton is assumed to lose all its energy by ionization and doesn't suffer any more collisions. Similar treatment is applied to accelerated α particles. In this case, the spallation reactions are $\alpha + \alpha \rightarrow$ ^{6}Li, ^{7}Li and α + CNO $\rightarrow$ ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B.

The simulation is run for various accelerated particle spectra and compositions of irradiated material. The compositions of 15M$_\odot$, 25M$_\odot$ and 35M$_\odot$ supernova ejecta (Weaver & Woosley 1993) are used as irradiated material distributed uniformly in a sphere of radius of 10^{15}cm. The source spectrum of

TABLE 2. Results for E_c = 100 MeV/nucleon, power law index n = 5 calculated for various supernova masses

	15M$\odot$	25M$\odot$	35M$\odot$	Observed
B/Be	16.4	12.9	12.5	10-20[1]
^{11}B/^{10}B	2.6	2.5	2.5	4.0[2]
^{7}Li/^{6}Li	1.5	1.5	1.6	12.6[2]
^{6}Li/^{9}Be	3.7	3.0	2.7	3.7[2]
$N_{\pi 0}$	2.0x10^{47}	6.5x10^{46}	4.4x10^{46}	
E_{sp} (GeV)	8.7	4.3	3.9	

1. Duncan *et al*. (1992) 2. Cameron (1982)

TABLE 3. Number of π^0s produced for various E_c (MeV) and n, calculated for 25M$\odot$ supernova

	E_c=50	100	200	500
n=5	0	6.5x10^{46}	1.5x10^{48}	2.8x10^{49}
n=10	0	0	3.4x10^{46}	1.8x10^{49}

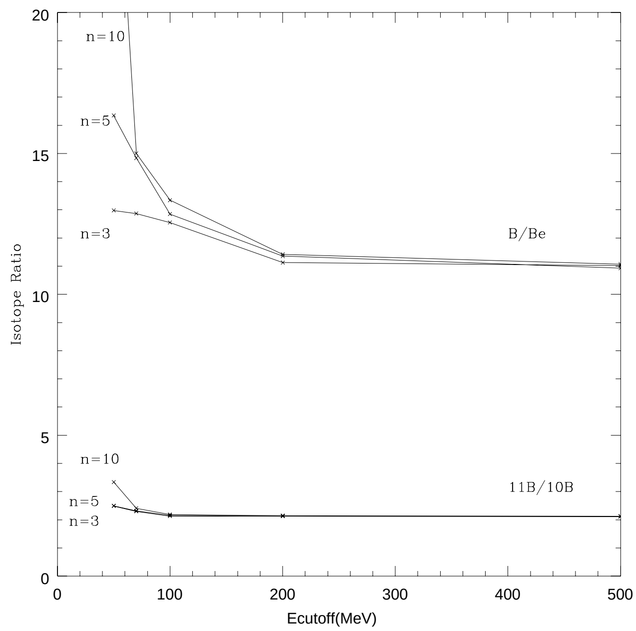

FIGURE 1. B/Be and $^{11}B/^{10}B$ for various cutoff energies (E_c) and power law index n using 25M⊙ supernova composition

accelerated particles is described as constant (flat spectrum) up to a certain cutoff energy E_c and at energies $E > E_c$, a power law decrease by index n. We use various cutoff energies (E_c = 50 MeV-500 MeV/nucleon) and power law indices (n = 2-10) and compare the results.

We calculate the total number of light element isotopes (^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B) produced by spallation in the irradiated ejecta, the total number of elastic and inelastic collisions and the energy needed per spallation (E_{sp}).

We find the energy per spallation (E_{sp}) to be in the range of 1-10 GeV, as shown in Table 1. The value of E_{sp} is higher in the case of E_c = 500 MeV/nucleon because the number of inelastic collisions is dramatically increased as the accelerated particle spectrum extends well beyond the 280 MeV threshold for inelastic collisions.

Using the Solar abundances (Cameron 1982), corrected for ^{7}Li to account for its production in the big bang nucleosynthesis, we get the total number of spallations per ^{56}Fe nucleus as 2.6×10^{-5}. The total amount of ^{56}Fe ejected from a supernova is taken as $0.07 M_\odot$, as observed in SN1987A (Erickson *et al*. 1988). Therefore the total number of spallations per supernova required for light element production is 3.9×10^{49}. Using 5 GeV as the value of energy per spallation, we get the total energy required as 3×10^{47} ergs. A typical supernova releases about 10^{51} ergs, so only a small fraction of the total energy needs to be directed towards spallation reactions.

The variation of B/Be and $^{11}B/^{10}B$ ratios with cutoff energy E_c and power law index n are shown in Fig. 1. The isotopic ratios $^{11}B/^{10}B$, $^{6}Li/^{9}Be$, $^{7}Li/^{6}Li$ and B/Be, the number of π^0s produced as a result of p-p inelastic collision and the energy required per spallation (E_{sp}), calculated for supernova masses of 15M$\odot$, 25M$\odot$ and 35M$\odot$ with accelerated particle spectrum as E_c = 100MeV/nucleon, index $n = 5$ are shown in Table 2. The observed isotopic ratios are also shown for comparison.

The B/Be ratio is recently observed in several Halo Dwarfs (Duncan *et al*. 1992, Boesgaard 1996) and is found to be in the vicinity of 10, which is consistent with our calculations. The Solar $^{11}B/^{10}B$ ratio of 4 is higher than our calculated value of 2.5. There may be other sources of ^{11}B production, such as neutrino induced nucleosynthesis in a type II supernova (Woosley *et al*. 1990), giving us the high $^{11}B/^{10}B$ ratio.

The energy required per spallation decreases with increasing supernova mass because the H/CNO ratio decreases with increasing supernova mass and so there are more spallation collisions and fewer elastic/inelastic collisions, thus utilizing more of the energy for spallation. For the same reason the number of π^0s produced decreases with increasing supernova mass.

Table 3 shows the number of π^0s produced for various cutoff energies E_c and index n, calculated for a 25M$\odot$ supernova composition. The threshold for π^0 production is at 280 MeV, so for certain accelerated particle spectra we get no pion production. The π^0s subsequently decay producing two γ rays at energies centered around 70 MeV.

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